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REPORT OF CELESTIAL OBSERVATIONS TAKEN AT KEY WEST, FLORIDA.

$4.60

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REPORT ON

PRECISION CELESTRIAL NAVIGATION EXPERIMENTS

CONTRACT # NONR - 2449 (00)

DATED 15 NOVEMBER 1957

This report covers the results of research conducted at Key West, Florida, and near Newport, Rhode Island, as well as afloat during the period January, 1958 through May, 1961

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JUNE, 1961

<u>REPORT</u>

In accordance with the provisions of O.N.R. CONTRACT NO. Nonr-2449 (00) dated 15 November 1957, celestial observations were obtained at Key West, Florida, during the period 8 February 1958 - 4 March 1958 and subsequently aboard the USS VALLEY FORGE (CVS - 45), the USS TUTUILA (ARG-4), the Yacht PARAMOUR and the Yacht RICKWOOD.

The purpose of this study was to determine what benefits could be derived from the use of high-magnification sextant telescopes (20x and 16x as well as 7x for use with the stars at dusk), what improvements could be made in the marine sextant and its ancillaries, and in the techniques of its employment.

Almost 5,000 celestial observations were made ~~in connection with this~~ program under conditions of visibility, weather, and quality of horizon ranging from excellent to extremely poor. The new instruments, ~~designed especially~~ for test during this study, as well as standard sextants and telescopes ~~presently in~~ general use were employed and compared under all manner of conditions such as might be encountered by the working navigator at sea. In fact, the frequency of observations made with a poor horizon was increased when it unexpectedly appeared that the high-powered telescopes under such conditions often gave materially more reliable altitudes than those in general use.

A number of experienced observers participated in this program: Capt. P.V. H. Weems, USN (RET.) and CDR. William S. Brown, USN assisted greatly in planning the study, and made many observations. Their advice and assistantance are particularly appreciated. Mr. G. D. Dunlap's help in preparing specifications for the Plath sextants and Beck tele-

scopes ordered especially for use in this program is also highly appreciated.

Early in the course of the study it became apparent that the accuracy of observations made with the high-powered telescopes was consistantly greater than that obtained with telescopes of 6x magnification, and much greater than that obtained with the 3x telescope in common use, particularly when the horizon was not sharply defined. (See figure 1.) This gain in accuracy was demonstrated by the plot of observations in each string, compared to the "line of best fit" for the string, as well as by the comparison of intercepts, when observations were made from an accurately known position. The results obtained with the 3x telescope were so obviously inferior to those obtained from a 6x telescope, that early in the study it was decided to use only the 6x glass for purposes of comparison with those of higher power, during daylight and bright twilight conditions. A very considerable number of observations of the stars were made at twilight with a dim horizon to compare the results obtained from the use of the best English and German 2x, 2.5x and 3x star telescopes, as against a 7 x 50 prismatic monocular. Under such conditions of poor horizon illumination, the 7 x 50 monocular was found very considerably superior to any other telescope tested.

It was found that the high-powered telexcopes enabled the observer to pick up a number of fixed stars within a few minutes of sunrise or sunset. For example, it was regularly possible with a 20x telescope to complete strings of observations of five or six stars at sunset well before these stars became visible in the field of the conventional sextant telescope. The resultant gain in accuracy, due to very good illumination of the horizon, was marked.

It has been hoped that the high-powered telescopes would permit the observation of some fixed stars between the hours of sunrise and sunset. It was found that this could occasionally be accomplished; however, it did not prove generally possible, due to the loss of brilliance of the star's image caused by the index and horizon mirrors. It seems probable that this difficulty can be overcome by redesigning the marine sextant to permit a direct view of the star, with the horizon becoming the reflected image.

During the study, it became increasingly evident that the great accuracy achieved by the high-powered telescopes in measuring the altitude of a body above the horizon made it most desirable to determine the value of the dip accurately and consistantly, which is not possible with the presently available tables. Even when the height of the eye was accurately established, anomalies in the value of the dip were encountered, although full allowance was made for barometric pressure, and air and water temperatures. Two Gavrisheff dip-meters were therefore obtained, one fitted with a 6x telescope, and the other with a 16x. The latter, particularly, gave excellent results, permitting the empirical establishment of the value of the existing dip with an accuracy, when it could be carefully checked, of about 0.1 minutes.

It is held that a well designed sextant, manufactured to the close tolerances possible today, and equipped with 20x and 7x telescopes, together with a dip meter, permits a very marked improvement in the accuracy of fixing position afloat by celestial means, as compared to that now possible.

SUMMARY OF FINDINGS

~~Findings of~~ this study ~~may be~~ is summarized as follows:

(1) The 20 x 50 mm prismatic monocular of good manufacture, is superior to any sextant telescope of lesser power during daylight hours. It reduces the random errors in a series of observations, as its great magnification permits the greatest nicety in obtaining contact between the body and the horizon. It is entirely satisfactory for use aboard ship except in extremely bad conditions of wind and sea.

(2) Similarly the 7 x 50 mm prismatic monocular is superior to any other telescope available for test when the horizon is poorly defined, due to darkness.

(3) A dip meter, fitted with a high power telescope, and capable of determining empirically the value of the dip to one-tenth of a minute of arc is an essential adjunct to the sextant, where accuracy is of primary importance.

EQUIPMENT AND TECHNIQUES EMPLOYED

The equipment employed to make the observations for this program falls into three categories: sextants, watches for the measurement of time intervals, and dip meters.

SEXTANTS: To obtain the observations for this study, five sextants were employed. All were of the micrometer drum type. One was a U. S. Navy Mark II Type A (Aluminum) instrument, one was a Hughes "Gothic" and three were manufactured by C. Plath. These latter three sextants were designed and manufactured for use in this study, and incorporated a number of new refinements. They had very large micrometer drums, and vernier scales calibrated to read to one-tenth of a minute; the scales were so large that they could easily be read to five one-hundredths of a minute. They were also fitted with large index and horizon mirrors which matched the full field of the 50 mm objective lenses of the scopes. The error in graduating the arc of the Plath sextants never is as great as 10 seconds; this also was a most desirable feature, as an error of up to 30 seconds is considered acceptable in ordinary U. S. manufacture.

Two of the Plath instruments had special light-weight alloy frames, the third Plath and the Hughes had brass frames, and were somewhat heavier; each weighed about 4 pounds 10 ounces. The alloy frame Plath weighed about 3 lb. 12 oz.. The heavier instruments caused no complaints. It was found that they vibrated much less, when being used in a breeze, than did the Navy Mark II sextant.

Interchangeable 6x, 16x and 20x prismatic monoculars were available for the Plath and Hughes sextants, as well as 7x monoculars and 2x and 3x

erect telescopes for use with the stars at dusk. All optics were hard-coated to permit maximum light transmission. Rubber eye cups were used with the high power telescopes; their use had a beneficial effect on the results achieved.

The Mark II Navy sextant was fitted with its only telescope, a 3x glass. During the course of the study, it became evident that the two telescopes holding the greatest promise were the 20x, for use at any time when the horizon was well illuminated, and the 7x for use with the stars, when the horizon was dim. Specifications were therefore drawn up with the assistance of Dr. S. G. Hall of the Naval Weapons Plant, Washington, D.C. for a prismatic monocular with a 50 mm objective, and interchangeable eye pieces, giving a magnification of 20x and 7x, respectively. This was manufactured by the firm Beck, of Kassel, Germany, who have had many years of experience designing and producing optics for telescopes. This telescope proved most successful, both on bench tests, and on the sextant.

The new Plath sextants and telescopes employed were found to be excellent and far superior to similiar equipment previously available. In expert hands they are capable of achieving an accuracy in determining the observed altitude considerably greater than that of the computed altitude obtained when the resultant observations are reduced by the Nautical Almanac and the modern navigational tables in common use afloat. These instruments also proved easier to keep in adjustment than the older type sextants.

Overall, with a bright horizon, the 20x telescopes proved slightly superior in accuracy to the 16x, and their greater power enabled the observer to pick up fixed stars somewhat more easily in a bright sky. Unfortunately, they do not have enough light gathering power to make them

satisfactory when the horizon is dimly lighted. Under such conditions, the 7x telescope proved superior to any glass previously tested. It is recommended, therefore, that when the utmost accuracy is required, a 20x telescope with 50 mm objective be employed when the horizon lighting is strong, and a similiar telescope, but of 7 power, be used when the lighting is weak. The single glass, with a 50 mm objective, and interchangeable 7x and 20x eyepieces proved most satisfactory.

The rapid determination of index error continued to be difficult, particularly during daylight hours, as it had for previous observers. This problem merits further study.

TIMING AND RECORDING: At all times during this program, multi-channel short-wave radio receivers were available, as were two highly reliable second-setting sweep second hand Longines watches. Observations were timed by split-second timers, reading to one-fifth second; these timers could be relied on not to vary one-fifth of a second in forty minutes, regardless of how many times the reading hand was stopped. An experienced observer can start these split-second timers on the WWV time tick with an accuracy of approximately one-tenth second. Whenever possible the times were started directly from the radio tick, and checked again with the tick at the termination of the observations. When, for any reason, the radio tick was not available, the timers were started from, and checked against the Longines watches. It is believed that the time error in only a few instances exceeded two-fifths of a second; for the great majority of observations, the error did not exceed one-fifth second.

The timing of observations by the recorders who assisted in this program

proved entirely satisfactory. The reaction lag of the two recorders who timed the majority of the sights was checked by means of a split second timer equipped to omit a short note when the stop button was pressed. Tests indicated that the lag rarely approached one-half second.

At Key West, a special watch was used, reading in arc to 360 degrees, and adjusted to sidereal time. This watch gave the local hour angle of Aries, and in conjunction with specially prepared altitude and azimuth tables of selected stars, proved most convenient for locating stars before they were readily visible.

Where the utmost accuracy is required, it is recommended that a remote recording chronograph be employed, combined with a remote read-out of the sextant altitude. This will obviate the possibility of error in the recording of time as well as error in the reading or recording of the altitude. In addition, it will greatly speed the taking of a string of sights, and the observer will not be faced with the danger of being unable to relocate a dim star, after reading the altitude; the sextant would be maintained in the observing position for an entire string of observation.

The chronograph should be so arranged that the second beat of the WWV time signal could be indicated on it when desired. It should also be possible to show the half-second beat of a chronometer, reading either Greenwich Mean or Sidereal Time. The altitude reading of the sextant would also be indicated on the tape, at the instant the time of the observation was recorded.

DIP METERS: Early in the program, it became evident that the new telescopes were capable of achieving a degree of accuracy in position fixing not previously obtainable with the marine sextant. If the true value of the

dip could be established. The depression of the visible horizon, below the horizontal at the eye of observer can readily be calculated. However, the line of sight from the observer to the horizon is affected by terrestrial refraction; the amount of this effect varies with changing weather conditions. Differences in air temperature along the line of sight from the observer to the horizon seem to be the chief cause of this variation. Where the water temperature differs from that of the mass of air above, the air immediately adjacent to the water is cooled or warmed. The effect of this difference is usually particularly strong on a calm windless day.

Many attempts have been made to establish a direct relationship between the difference of temperature of air and sea and the value for the correction for dip, however, the results obtained by different investigators differed so greatly that no definite conclusions can be drawn. It seemed most desirable, therefore, to determine the value of the existing dip empirically at the actual time of making celestial observations. For this purpose, two Gavrisheff dip meters were procured, one fitted with a telescope giving a magnification of 6x, the other with one of 16x. Both instruments proved to be of the greatest value, the one with the 16x telescope giving the better results. In the interests of standardization, a 20x telescope is recommended for future use with the dip meters.

The Gavrisheff dip meter measures the value of the dip by bringing into coincidence two images of the horizon, one erect and one inverted, and 180° apart in azimuth. The instruments employed in this study were fitted with micrometer drums, and vernier scales calibrated to two tenths of a minute of arc. They could be read to one-tenth of a minute by interpolation. An

excellent feature of the Gavrisheff design is that index error can be cancelled by rotating the instrument through 180° about the optical axis of the telescope.

These dip meters were not available during the period when observations were made at Key West; they were first used aboard the USS VALLEY FORGE in January 1959 and their value immediately became apparent. Considerable differences between sea and air temperatures were encountered, and had a marked, but by no means consistant effect on the dip. This can be seen from the following tabulation, which presents a portion of the dip measurements made. In each instance the dip by meter represents the average of a number of measurements.

3 Jan. 1600 O-1 level, air 48°, water injection 6[illegible]°

Dip by meter, observer S 7.25 minutes

Dip by meter, observer W 7.2 minutes

Dip by tables 5.8 minutes

4 Jan. 1015 O-[illegible] level, air 53°, water injection 68°

Dip by meter, observer S 6.5 minutes

Dip by meter, observer W 6.45 minutes

Dip by tables 5.8 minutes

In view of the 15° difference between sea and air temperatures, it seemed that the dip as measured by the meter was [illegible] in this instance, and it was measured from another level, with the following result.

4 Jan 1040 0-6 level, Temp. as above

Dip by meter observer S 9.625 minutes

Dip by meter observer W 9.6 minutes

Dip by tables 8.9 minutes

9 Jan. 1100 0-6 level, Air [illegible], water injections 70°

Dip by meter observer S 8.7 minutes

Dip by tables 8.9 minutes

Such celestial observations as could be obtained during this period, when corrected for dip as obtained by the dip meter, always resulted in lines of position lying much closer to Loran fixes than those corrected by means of the dip tables.

During this same cruise the USS VALLEY FORGE lay-to some 7 miles from Bermuda, where her position could be accurately fixed by triangulation and radar ranges. Sun sights were obtained, and reduced from the known position. Using the value of the dip as obtained by dip meter in correcting the altitudes, the mean distance from the known position was 0.115 miles; when the tabulated value of the dip, corrected for barometric pressure and temperature was employed, the mean distance was 0.85 miles.

These anomalies in the value of the dip are particularly interesting, as the winds were extremely strong (up to 65 knots) during much of this period, and because many of the dip measurements were made with a height of eye of over 80 feet. Both of these factors are supposed to reduce any anomalies in the dip at sea.

Aboard the USS TUTUILA, in August of 1960, a diurnal variation of one minute was found in the dip by measurement, without appreciable changes in barometric pressure and sea and air temperatures. This variation persisted over several days, the value of the dip being one minute greater in the afternoon and evening than in the morning. That this anomaly existed was also demonstrated by the plot of morning and evening star sights; the lines of position resulting from evening stars each having to be moved one minute towards the respective bodies to cross close about a common point.

There seems little doubt that a dip meter of the quality of the Gavrisheff instruments is of the greatest value in determining the value of the dip, and consequently improves materially the accuracy of celestial navigation.

It cannot correct for error caused by the tilt of the horizon, or for the transitory effect of a wave in the horizon, but it will permit accurate correction of much the greater part of the errors caused by abnormal terrestrial refraction.

It should be noted that the dip meter fitted with the 16x telescope gave materially better results than the one with the 6x telescope. Consecutive readings in each string gave more consistent readings, the magnitude of the random errors being materially reduced.

<u>OBSERVATIONAL TECHNIQUES:</u> It was held that the maximum diameter of the objective lens of any telescope to be used with a sextant would be 50 mm; anything larger than this would be too large and clumsy to handle conveniently aboard ship. As the field of view of a prismatic telescope of normal design with an objective lens of this diameter and giving a magnification of 20x is about 3 degrees, it was apparent that the Rude Star Finder

would not be sufficiently accurate for locating stars, particularly at the higher altitudes, in a brightly lighted sky. Accordingly, for use at Key West, the altitude and azimuth of 6 morning and 7 evening stars were computed for 30 degrees of Local Sidereal Hour Angle. These altitudes and azimuths were precomputed to the nearest minute of arc, spanning the times of sunset and sunrise for the period of field work. In conjunction with the watch mentioned above, reading in Local Sidereal Hour Angle, and an 8 inch spherical magnetic compass, these tables greatly facilitated locating the stars against a bright sky. The stars for which the Key West altitude and azimuths were precomputed are as follows:

Morning:		Evening:	
Altair	(Mag. 0.9)	Aldebaran	(Mag. 1.1)
Antares	" 1.2	Betelgeux	" Var.
Arcturus	" 0.2	Capella	" 0.2
Deneb	" 1.3	Pollux	" 1.2
Spica	" 1.2	Procyon	" 0.5
Vega	" 0.1	Rigel	" 0.3
		Sirius	" 1.6

The times of sunrise and sunset of Key West for the period of observations were also computed.

Altitude and azimuth data as outlined above were also prepared for all subsequent twilight star observations, although not to such close tolerances. These were frequently presented in graphic form.

Most of the observers connected with this program were accustomed to using the somewhat heavier Plath and Hughes sextants. The 20x and 16x telescopes with their very considerable magnification, and comparatively small field however, were new to all save one observer, and several hours of practice were required before the users became accustomed to them. The

apparent magnification of vibration with these telescopes particularly caused adverse comment at first, and the observers believed that the plots of their strings of sights made with the high powered glasses would be inferior to those made with a 6x monocular. It always proved a source of surprise to the observer to find, when the sights were plotted, that the strings of observations made with the higher powered glasses were considerably smoother than those made with the 6x telescope. Without exception, once the observers became accustomed to the new glasses, they preferred them to those of 6 power, when accuracy was particularly required.

Tests were made using a bipod to support the sextant, which was mounted at the apex, while the two legs attached to the observer's belt. This device was not found to be practical. Thought was also given to mounting a sextant on a gun stock and also to suspend it from a gallows frame, but no experiments were conducted with such devices.

No unusual techniques were employed in making the observations; every effort was made to take the sights in each string as rapidly as possible. When two observers were working at the same time, simultaneous observations of the same body would frequently be made, one observer using a 20x telescope, and the other a 6x. At the completion of each string of sights telescopes (but not sextants) would be exchanged. When one observer was working alone with a recorder, one string would be completed with one telescope, and the next one with a glass of different power. The value of the high powered telescopes, as compared to those giving a magnification of 6x, for picking up stars during "bright sky" conditions also was studied, and is discussed below.

A string of sights normally consisted of 10 to 13 observations; accuracy tends to deteriorate after about that number, apparently due to eye fatigue. However, a very brief rest for the eye was sufficient to restore accuracy, and frequently 10 to 12 strings would be observed over a period of about an hour. Where the same conditions of lighting and weather persisted, the last string would generally plot as smoothly as the first, provided a brief period had been allowed between strings.

All strings were plotted on graph paper, using a scale of 1 inch to 10 seconds of time, and when the rate of change of altitude was not too great, 1 inch to 1 minute of arc; occasionally, it was desirable to change the latter to 1 inch to 2 minutes of arc. The strings were completed in between 2 minutes 30 seconds and 3 minutes 30 seconds. Due to the smaller field of the 20x telescope, it was found that overall the time between sights with this glass tended to be slightly longer than when using the 6x. This time difference would not exist if a sextant with remote altitude read-out were employed with the 20x telescope, as the observer would not have to relocate the body after each individual observation.

After the sights were plotted, a line of best fit was drawn through the plots; due to the shortness of the time period involved, a straight line gave a satisfactory representation of the body's path. The rate of change of altitude for the body at the mid time of the string was than calculated, to check for possible anomalies caused by terrestrial refraction, or other causes. Such anomalies, affecting the rate of change of altitude, were occasionally encountered.

When working from a position that could be accurately established, us-

ually by triangulation, the calculated altitudes of the body for the site, corrected for dip, refraction, etc., for the time of the string, would then be plotted on the graph. The deviation of the individual sights from the line of best fit for each string would be measured for comparison purposes, as well as the difference in altitude between lines of calculated altitude and the lines of best fit. As has been stated above, the results achieved with the high powered telescopes were superior almost without exception; the rare exception occurring when observational conditions were deteriorating, and the high powered glass was the last one used.

The magnitude of the random errors about the line of best fit was consistently and materially less for the high powered telescopes, as was the difference between the line of best fit and the line of calculated altitudes. The superiority of the high powered telescopes was particularly great when the horizon was not sharply defined.

Key West was not found to be a very satisfactory locale for the purposes of this program, as the water mass inshore is not homogeneous. A considerable number of surface water temperature measurements were made 4 to 5 miles offshore (i.e. at the approximate apparent horizon of the observer on the beach), and the temperature was found to vary as much as 10°F. within 200 yards. In this connection it may be noted that some 30 strings of sights were made from aboard a 46 foot sailboat 40 to 60 miles offshore in waves up to 6 feet in height. The resultant intercepts varied less in magnitude than many of those made from the beach at Key West; apparently the boat was surrounded by water of the same temperature.

Mechanical vibration, as in a destroyer steaming at 20 knots, did not

have a markedly adverse effect on the smoothness of the plot of sights. The high powered telescopes produced consistently better results than those with a magnification of 6x, despite the firm conviction of the less experienced observers that the contrary would prove true. High winds, as are often found on the open bridge structure of a carrier, made it extremely difficult to obtain satisfactory observations with any telescope.

<u>EFFECT OF SEAS:</u> Sights were reduced by various methods, as seemed appropriate. Where the utmost accuracy was desired, the Ephemeris was used together with the classical sin-cos altitude and azimuth formulae. Six-place natural functions were used with a computer. Where extreme accuracy was not of prime importance, the Nautical Almanac and the Tables of Computed Altitude and Azimuth (HO 214) were employed. The Delta t and Delta l corrections, as well as Delta d, were usually used to reduce the length of the intercepts. All sun sights were corrected for the actual semi-diameter, parallax, and for refraction; the combined semi-annual tables in the Nautical Almanac were not used. For all sights, the table of "Additional Refraction corrections for Non-standard Conditions", published in the Nautical Almanac, was used as required. Before the dip meters became available, the Japanese tables for correcting for the difference between air and sea temperatures (0.11 minutes per degree Fahrenheit) were also employed, and in the majority of cases proved helpful. The corrections they provided in general shortened the intercepts, and in the geographical area of this study, off the eastern seaboard of the United States, were superior to any other similiar tables used. However, the accuracy they provided did not equal that achieved with the dip meter.

It had been hoped that the brighter fixed stars, favorably situated in altitude and azimuth relative to the sun, would be visible during the day in the field of a high power telescope, mounted on a marine sextant. This hope was based on a paper entitled "The Visibility of Stars in the Daylight Sky" by Dr. Richard Tousey and E. O. Hulburt, and published in the Journal of the Optical Society of America, Vol. 38, No. 10 Oct. 1948. Consultations with Dr. Tousey at the Naval Research Laboratory were held, and confirmed that fixed stars could be observed during daylight hours with a well designed telescope, having a magnification of 16x or 20x, particularly if the telescope were provided with a reticle at infinity to aid the eye in maintaining focus at infinity. It also appeared that it would be desireable to provide a polarizer for the telescope in connection with these observations. The reticles were accordingly installed, and polarizers were provided.

These telescopes did indeed make it possible to pick up stars, when viewed directly, during the daytime. However, no real success can be claimed when the telescopes were mounted on sextants, although Sirius was picked up low to the eastward on two occasions about 15 minutes before sunset and Arcturus was seen at high altitude 25 minutes after sunrise. The light loss in reflecting the star's image through the index and horizon mirrors was too great to make daytime star observations practicable with the sextant in its present form.

The high-powered telescopes did, however, make it possible to observe a very considerable number of fixed stars in bright twilight, when they could not be sighted with a 7x or 6x telescope. These latter glasses,

in turn, proved superior in this respect to the 3x telescope as supplied with the Navy Mark II sextant. At Key West, strings of observations totaling between 40 and 60 sights were completed of 4 to 5 stars with a 20x telescope, within 20 minutes of sunset; that is to say, with the 20x telescope, the observations for the evening star fix were completed at about the time a navigator using the ordinary sextant and telescope would start making his observations.

Similiarly, on 30 August, 1960, in approximately latitude 30° N., Long. 79° W, 5 stars, as tabulated below, were sighted with a sextant fitted with a 20x telescope within 10 minutes of sunset.

Star	Magnitude	Apprx [illegible]	Apprx. Azimuth
Altair	0.9	46	110
Antares	1.2	34	194
Arcturus	0.2	50	265
Deneb	1.3	45	054
Vega	0.1	69	160

Stars observed under such conditions, with a well illuminated and sharply defined horizon, yielded far better results than those made in deeper twilight with a 6x or 7x telescope. However, with the sun well below the horizon, the 7 x 50 monocular proved superior in every respect to any other telescope employed. Its large field, excellent light transmission, and sharpness over the entire field, are most desirable features for this use. It should be noted that the 7 x 50 telescope is not satisfactory for daytime use with the sextant, particularly for sun observations. During such observations,

there is frequently a very strong and troublesome halation effect.

<u>ACCURACY</u>- The degree of accuracy obtainable with the instruments employed during this program in measuring both time and altitudes and in establishing the value of the dip is so fine, that thought must be given to improving the methods employed in reducing sights. The American Nautical Almanac, under the heading "Accuracy" says in part:

"The largest error that can occur in the G. H. A. or Dec. of any body, other than the Sun or Moon is less than 0.2 minutes; it may reach 0.25 minutes for the G. H. A. of the Sun and 0.3 minutes for that of the Moon.

In practice it may be expected that only one-third of the values of G. H. A. andDec. taken out will have errors larger than 0.05 minutes and less than one-tenth will have errors larger than 0.1 minutes."

It should be added that these errors in Greenwich Hour Angle and Declination may be cumulative, thus causing a considerable total error. As the time of an observation can be accurately determined to one-fifth of a second, it is most desirable to be able to determine the G. H. A. of the body at the instant of observation with an accuracy of 0.05 minutes of arc.

The high-power telescopes make Venus available for daylight observation during much of the year, yet corrections to the altitude of this planet for parallax and phase for such observations are not given. The semi-diameter of Venus should also be given, as in the field of a 20x telescope the planet is not a joint of light, but has very appreciable size.

Where accuracy is paramount, it is recommended that observations be reduced from the estimated position, rather than from an assumed position.

Smart, "in the Monthly Notices of the Royal Astronomical Society", Vol. 79, (May 1919) showed that when the difference between the true and assumed positions is 30 minutes in both latitude and longitude, for an altitude of 75 degrees the error might be 1.0 miles. At latitude 60 degrees this would diminish to 0.7 miles; while the probable error would not exceed 0.3 miles. It can be seen, therefore, that plotting celestial observations from an assumed p may introduce unacceptable error.

The "Tables of Computed Altitude and Azimuth" (H.O.214) are among the most satisfactory of the so-called "short methods", and are excellent for most navigation. However, they also can cause unacceptable error, even though the DeltaTand Delta L corrections are used in addition to that for Delta d. For example:

On page 509 of the 1958 edition of Bowditch (H09) the calculated altitude 20 degrees 55.9 minutes is obtained using HO 214 and the corrections Delta d, Delta t and Delta L. The correct answer is 20 degrees 55.67 minutes.

It is evident therefore that the methods commonly employed at sea for the reduction of celestial observations are not compatible with the degree of accuracy obtainable with the instruments discussed herein. The Ephemeris is available in lieu of the Nautical Almanac and gives the necessary data to a degree of accuracy far beyond that required at sea. However, its presentation is designed for the astronomer, and necessitates long and cumbersome interpolations. Probably the most desirable form for presenting the necessary data would be to state Greenwich Hour Angle, Sideral Hour Angle, and declination in degrees, minutes, and hundredths of minutes. For some bodies, to facilitate

interpolation, it might be well to state Greenwich Hour Angle for some period shorter than an hour.

An electronic computer can, of course, store the necessary data on the celestial bodies to be observed during any program, and can also r the observation. Where such a device is not available, the formulae:

$$\text{Sin } h = \sin L \quad \sin d \pm \cos L \quad \cos d \quad \cos t$$

$$\text{and} \qquad \text{Sin } Z = \frac{\cos \quad d \qquad \sin \quad t}{\cos \quad h}$$

give excellent results, and a speedy reduction, when used with six or sev place tables of natural functions, and an ordinary desk computer. Precom will frequently be most desirable.

A string of observations of each body should be made; this can be done rapidly, particularly where the remote read-out of time and altit are employed. Such a series of 10 to 15 observations, when plotted, permits the rejection of unsatisfactory individual sights, as well as the de of transient anomalies, such as waves in the horizon. It also permits an evaluation of the probable accuracy to be derived from the reduction of t selected observation in the string.

The observer should be selected for his visual acuity: he need have no knowledge of navigation. In this connection, it may be noted tha some of the best strings of observations obtained during the course of th study, were made by young observers who had never previously used a sexta They had good vision, and they were also free of prejudice against the hi power telescopes. An expert marksman frequently seems to make an exceller observer.

CONCLUSION

1. It is held that the high powered telescopes, of a magnification of about 20x, when fitted to sextants of the highest quality, and which allow a fine read-out of altitude, permit achieving a markedly superior degree of accuracy than has heretofore been possible with the instruments in general use.

This improvement in accuracy is derived from three characteristics of the high powered telescopes:

A. Their increased magnification permits the greatest nicety in making contact between the body and the horizon.

B. Their high magnification makes fixed stars visible in comparatively bright light, just before sunrise and directly after sunset, when the horizon is sharply defined.

C. In the great majority of instances, during daylight hours when the horizon is hazy, they permit markedly better determination of the horizon than do the telescopes of 3x and 6x in general use.

It appears from this study that the accuracy achieved in measuring altitudes with the sextant is in direct proportion to the magnification of the sextant telescope. A 20 x 50 prismatic monocular, of good design, at present seems to be the optimum for use with a bright horizon. The degree of accuracy achieved by such a telescope far outweighs the dis-

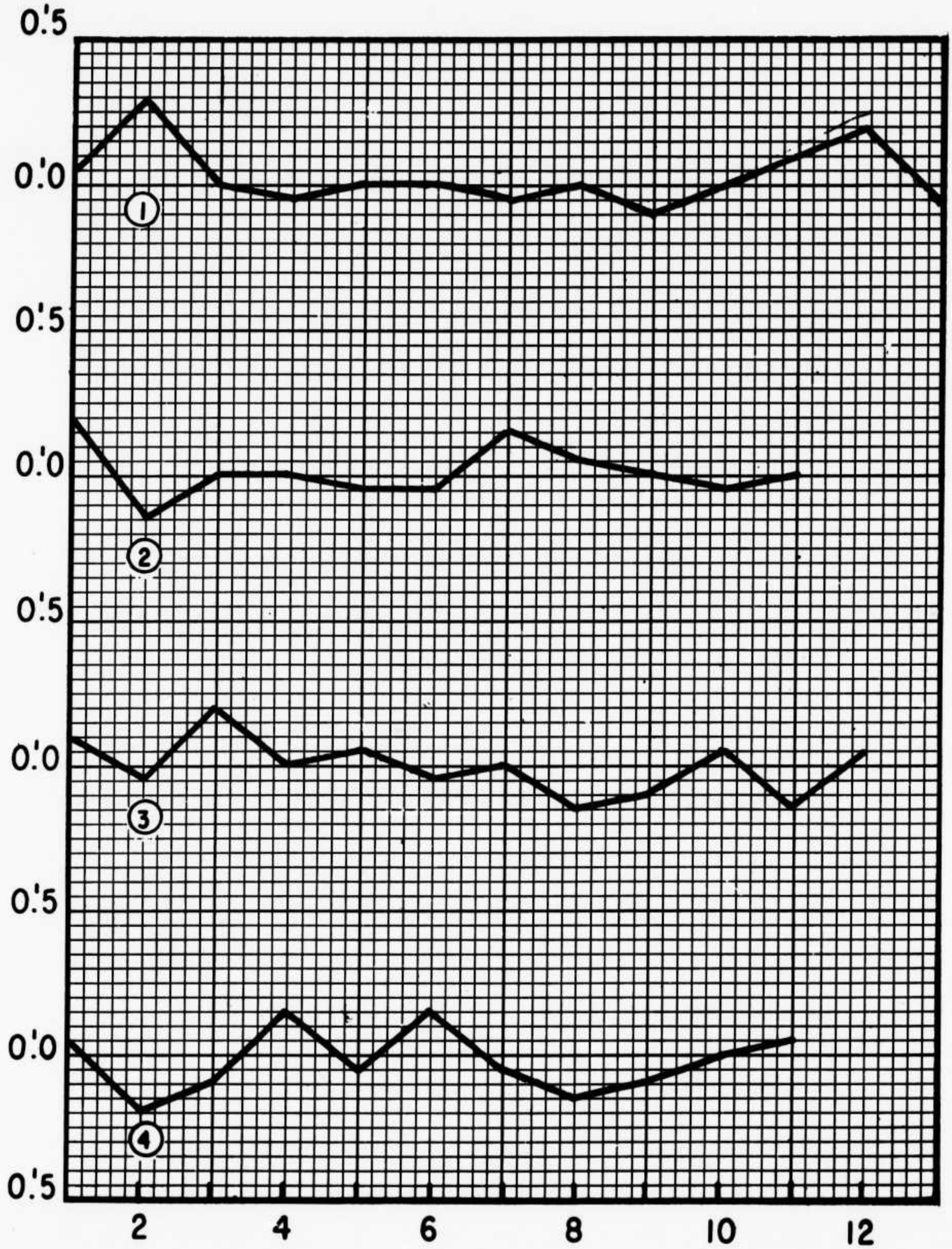
advantages of its comparatively small field and increased weight.

2. At twilight, when the contrast in lighting at the horizon is not strong, the 7 x 50 monocular is found to be superior to any star telescope now in general use.

3. A Gavrisheff dip meter, fitted with a high power telescope can be of the greatest assistance during daylight hours in determining the existing value of the dip of the horizon, and therefore in increasing the accuracy derived from daytime observations of the sun, moon, and plan

4. Finally, it is held that a ship's position may be fixed at sea, under good observational conditions, to about 0.25 miles, by a round of multiple observations of stars, made just before sunrise or after sunset, with a high quality sextant, fitted with a 20x telescope. This conclusion is based on the results achieved during the course of this stu Remote read-out of sextant altitude and time should improve this somewhat.

With 6 x and 3 x star telescopes, it has heretofore been possib under similar conditions to obtain an accuracy of about 0.4 miles.



0.'5
0.'0
0.'5
0.'0
0.'5
0.'0
0.'5
0.'0
0.'5
1
2
3
4
2
4
6
8
10
12

THE 20x TELESCOPE FOR STAR SIGHTS.

THE 20x TELESCOPE FOR STAR SIGHTS

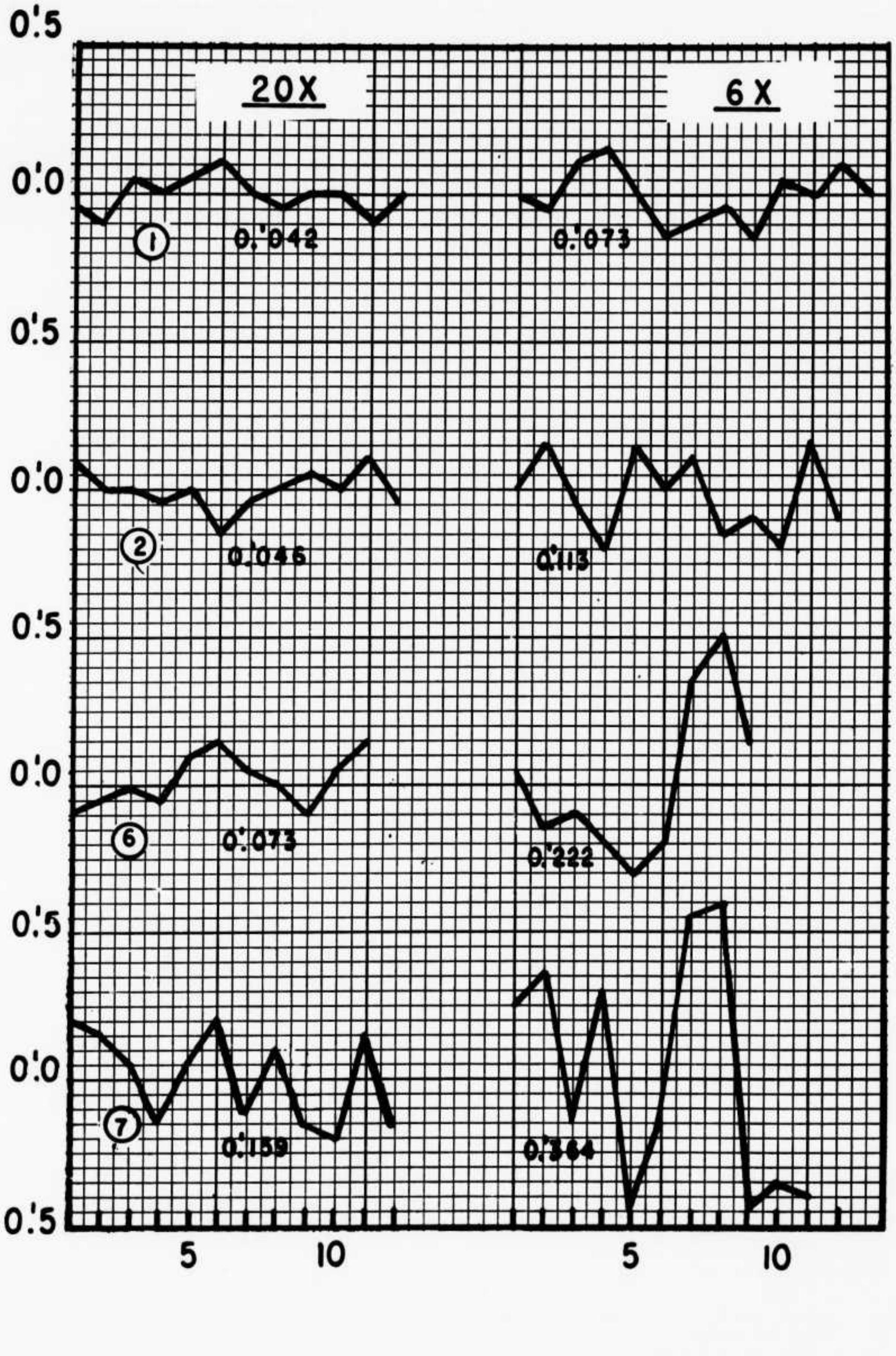
On the opposite page are the plots of four strings of star observations, made with a 20x telescope on the eveninggof 3 March 1958. The stars, in the order in which they were observed, are Sirius (-1.6), Aldebaran (1.1), Betelgeux (Var.) and Rigel (0.3). The first observation of Sirius was made directly after the sun had set, the last observation of Rigel was completed some 18 minutes later.

No direct comparison between the 20x and the 6x telescopes were possible, as the observer using the 6x glass was unable to pick up the stars concurrently.

The mean aberration from the line of best fit of the Sirius observations is 0.069 minutes, for Aldebaran 0.064 minutes, for Betelgeux 0.079 minutes, and for Rigel 0.095 minutes.

These observations serve to show the high degree of accuracy that can be expected from star observations, made with a high-powered telescope during the period that the horizon is brightly illuminated.

The time interval between observations is plotted as constant.



0'.5
20X
6X
0'.0
1
0'.042
0'.073
0'.5
0'.0
2
0'.046
0'.113
0'.5
0'.0
6
0'.073
0'.222
0'.5
0'.0
7
0'.159
0'.364
0'.5
5
10
5
10

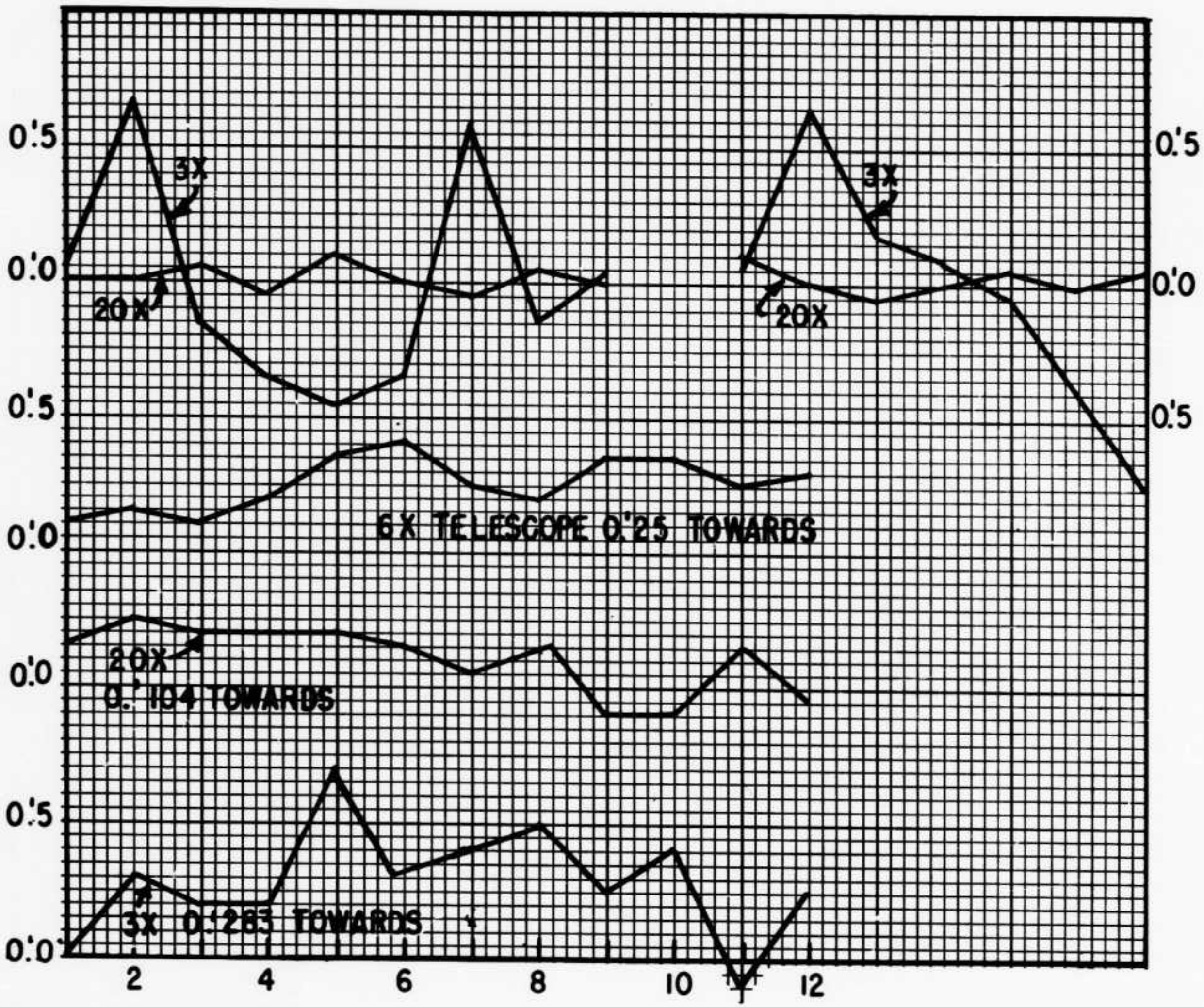
COMPARISON OF OBSERVATIONS OF THE SUN MADE AT SEA WITH 20x AND 6x TELESCOPES

On the facing page appear graphs showing the aberration from the "line of best fit" of individual observations within strings of Sun sights, made at sea with 20x and 6x telescopes. The mean aberration for each string is noted below.

These graphs show the first two and the last two pairs of strings cited in Section A of Appendix I.

The observations in each pair of strings were made by one observer. When the string was completed with one telescope, the latter would be changed as rapidly as possible, and the second string of the pair would be completed.

The time interval between observations is plotted as constant.



0'.5
0'.0
0'.5
0'.0
0'.0
0'.5
0'.0
3X
20X
6X TELESCOPE 0'.25 TOWARDS
20X
0.'104 TOWARDS
3X 0'.283 TOWARDS
2
4
6
8
10
12

COMPARISON OF SIMULTANEOUS OBSERVATIONS OF THE SUN MADE AT SEA WITH 3x AND 20x TELESCOPES: 3x AND 20x TELESCOPES

The graphs on the opposite page illustrate results obtained aboard the U.S.S. TUTUILA. These observations were made at about 1030 Zone Plus Five Time on 18 May 1960, some 100 miless S.E. of the Virginia Capes, by two experienced observers. Simultaneous observations were made of the Sun's lower limb, one observer using a Plath sextant fitted with a 20x telescope, the other a U. S. Navy Mark II sextant with a 3x telescope, as supplied with the instrument.

On completing the first string of sights, the observers exchanged sextants, and the second string of observations was made.

There was some overcast, which accounts for the rather short second string. The wind was S.W., Beaufort scale #3, the state of the sea was #3, and with the 3x telescope, the horizon appeared very "fuzzy".

On the lower part of the page appear the plots of three consecutive strings of Sun sights, made with a 3x, 20x, and 6x telescope in that order by the same observer, from a known position. The 3x telescope placed the observer 0.283 minutes too much towards the sun, the 20x made it 0.104 towards, and the 6x 0.250 towards. The horizon on this occasion was not sharply defined.

The time interval between observations is plotted as constant.

APPENDIX I

The following tabulations show in numerical form the smoothness of plot of strings of observations using alternately a 20x and a 6 x telescope with the same sextant. It gives an indication of the improvement in accuracy made possible by the high powered telescope. These observations were made during the daylight hours, by a number of observers. Some were made from the beach, and some at sea; they were made under widely differing observational conditions. The majority were of the sun, although observations of the moon and of Venus are also included.

A string of observations, usually between 10 and 14 in number, would be made with one telescope, which would then be changed for one of different power. The altitudes were plotted, as described in the body of the text, and the "line of best fit" was drawn for each string. The deviation in altitude of each individual observation from the line of best fit was measured to the nearest five-one hundredths of a minute, and these deviations were then added, regardless of sign. The sum of the deviations in each string was then divided by the number of observations in the string, to give the various results listed below.

The results are arranged in two groups, according to whether the observations were made afloat, or from the beach. Many observations were made when the horizon was very poorly defined, in order to obtain data on the performance of the high power telescopes under such conditions. However, no criteria are available for grading the quality of the horizon for observational purposes. It seemed best, therefore, to make an arbitrary

arrangement in descending order of the values of results obtained with the 20x telescopes. The poorest, as well as the best results achieved are included in the tabulation.

Graphs appear elsewhere in this report, which illustrate the distribution of sights within some individual strings listed below, as well as in strings not made for direct comparison purposes between various telescopes.

A. OBSERVATIONS AT SEA

	20x telescope	6x telescope	Body
1.	0.042	0.073	Sun
2.	.046	.113	"
3.	.050	.138	"
4.	.054	.192	"
5.	.061	.108	"
6.	.073	.222	"
7.	.159	.364	"

B. OBSERVATIONS FROM THE BEACH

	20x telescope	6x telescope	Body
1.	0.027	0.060	Sun
2.	.031	.089	Venus
3.	.036	.078	Sun
4.	.058	.054	Moon
5.	.063	.127	Sun
6.	.077	.227	"
7.	.083	.123	"
8.	.085	.323	"
9.	.092	.273	"

	20x telescope	6x telescope	Body
10.	.119	.716	Sun
11.	.127	.196	"
12.	.138	.200	"
13.	.150	.231	"
14.	.162	.265	"
15.	.173	.327	"
16.	.178	.112	"
.17	.204	.373	"

APPENDIX II

RESUME OF RECOMMENDATIONS

Various recommendations are made in the body of this report; they are outlined below. Additional recommendations are also included, not necessarily in the order of suggested priority.

I. THE SEXTANT

It is doubtful if the basic design of the sextant can be improved for ordinary marine use. However, it can undoubtedly be improved in detail, and modified for specialized use, in order to gain improvement in accuracy. Few improvements have been made in the sextant during the past three quarters of a century; it is time that a thorough study of the instrument, as a tool for celestial navigation, be initiated.

Set forth below are suggestions as to some of the matters which might be included in such a study.

A. 1. For celestial navigation, particularly where accuracy is important, a sextant with minimal constant or non-adjustable error is required. In the past, the standards of required accuracy have been too low. In this country, a constant error of 30 seconds has been permissible, and an instrument with a maximum error of 15 seconds has been considered superior.

It is recommended that the value of the maximum permissible constant error be redetermined for sextants intended for refined celestial observations. It is suggested that this maximum error be established as [illegible] seconds. Such a standard is not too high, and can be achieved under modern

production methods. For example, the certificate of Plath sextant #39393, used in this program, shows the following constant errors:

Altitude	10	20	30	40	50	60	70	80	90	100	110
Error in seconds	0	+1	+3	+2	-1	+1	-1	-4	-6	-3	0

2. For celestial navigation, an instrument is required that measures angular elevation to 90 degrees. "Back sights" are now rarely used, and a sextant capable of measuring angles to 145 degrees or thereabouts is not needed. It is possible that an instrument in the shape of an octant measuring angles to 90 degrees might be more convenient to use. This ~~means~~ requires study. At the same time, it should be determined whether mechanical accuracy could be improved by increasing the radius of the arc. The design of a sextant, intended for the daylight observation of stars is discussed below.

3. The design of sextant mirrors also warrants study. These should, of course, be of a size compatible with the field of the telescope employed. It would seem that the use of a front coated mirror would be most desirable; particularly for the index mirror. With the conventional "back coated" mirror, particularly at high altitudes, the light from the body is diminished materially by the considerable thickness of glass through which it must pass. The development of such front coated mirrors for use on the sextant, seems most desirable. If front coated mirrors are not employed, the horizon mirror should be positioned in such a manner relative to the index mirror that light rays from a body, observed at high altitude are not at an excessively acute angle to the latter mirror. The more acute this angle is, the more attenuated are the light rays as seen by the observer. It might be

well to place the horizon mirror forward of its normal position on the instrument.

4. The clear glass portion of the horizon mirror does not appear to fulfill any useful purpose. It, also, absorbs light, particularly when particles of salt adhere to it. Some experienced navigators have this clear glass portion removed from the mirror, this would seem advantageous.

5. Various prisms have been fitted on sextants, particularly for star observations. Astigmatizers have been employed, which turn the image of the star into a line; these are sometimes helpful when the star is bright, and the horizon is poorly lighted. Under these same conditions a Wolaston prism can also be a help. This gives two images of the star, separated by about 5 minutes of arc in the vertical plane, the true position of the star being half-way between the two images.

The Van Leeuwen prism has been used with great success for sun observations with fine transits. It seems possible this prism might prove equally satisfactory when used with a sextant. The center of the sun is, in effect, observed on the horizon, and there would be no danger of error due to irradiation effect, and no correction would be required for the sun's semi-diameter.

6. Variable density polarizing shade glasses are at present standard on U. S. Navy sextants. Opinion as to their superiority over a series of neutral tinted shades, graduated in value, is divided. Under certain conditions, as when observing a brilliant star against a dim horizon, a conventional [illegible] shade, of rather low light absorbtion, seems superior to the

variable density type; some observers prefer the conventional shades under all conditions. It is recommended that the two types of shades be evaluated under service conditions.

During a study of terrestrial refraction in Chesapeake Bay made by the Naval Research Laboratory NRL Problem N03-05, Project No. NC284-512, it appeared that a red filter could at times be helpful in making observations of the horizon. The benefit to be derived from using horizon filters of various colors warrants study. During this program, it was found that under certain conditions of low contrast between sky and water, a single polarizing shade, of low light absorption gave a well defined horizon.

It may be noted that most sextants do not have enough horizon shades to permit proper adjustment for various degrees of horizon lighting.

7. For star observations with the sextant at dusk, it is most desirable that there be a convenient method of adjusting the position of the horizontal axis of the telescope, relative to the frame of the sextant. Moving the telescope out from the frame increases the ratio of light from the horizon, relative to that from the star. Most sextants incorporate some provision for accomplishing this; usually, however, it cannot be done readily. The Hughes "Gothic" sextant has a large thumb screw, so situated that the observer can easily turn it with his thumb, while holding the sextant to his eye. It is recommended that this feature be incorporated in all marine sextants.

8. During daylight hours particularly, it is difficult to establish accurately the sextant index error. It is recommended that this problem be studied.

B. The design of telescopes for use with the sextant warrants study. For daylight use, the 20x telescopes used in this program seemed more satisfactory, on the whole, than those of 16x. However, it may develop that better results can be achieved with a telescope of either greater or lesser magnification than 20x. Whatever the power of such a telescope, it should have as large a field as possible, with sharp focus over the entire field, and excellent light transmission characteristics; the sextant mirrors would, of course, be of an appropriate size.

Similarly, the characteristics of the optimum telescope for use at dusk should be determined. The 7 x 50 telescopes used proved superior to any of the star telescopes generally available, but here again, further improvement is probably possible.

Interchangeable eye pieces for use with the same telescope reduced the amount of equipment required for this program. The possibility of developing sextant telescopes with interchangeable eye pieces should be studied.

All sextant telescopes should be equipped with soft rubber eye cups; they are of great importance with high power telescopes. These enable the observer to steady the sextant against his eye socket, and keep wind and stray light from his eye. The eye cups that are available commercially are not too well suited for this purpose. It is recommended that a cup be designed especially for use with the sextant telescope.

C. The remote read-out of sextant altitude, plotted against time, would be of great advantage. It would remove the chance of human error in noting time and altitude, and would very markedly decrease the time required to complete a string of observations, as the observer would not be required to lose sight of the star, while reading the sextant altitude.

When such a read-out is employed, study is warranted to determine the period of time that should be spent in completing any one string of observations. While anomalies in refraction, lasting for considerable periods of time sometimes occur, transient anomalies causing considerable error in the observed altitude also are encountered. These latter anomalies, lasting usually less than a minute can usually be detected if frequent observations are made over about a two minute period. A string of some six observations, or so made rapidly, can be very misleading, however. While the altitudes may plot smoothly against time, they do not represent the true change of altitude of the body.

D. It is recommended that a sextant be developed for the daytime observation of fixed stars in conjunction with a high-powered telescope. Dr. Richard Tousey, of the Naval Research Laboratory, has shown that stars of the first magnitude, properly situated, can be seen during daylight hours on a clear day (Journal of the Optical Society of America, Vol. 38, No. 10, pp. 886-896, October, 1948) On 13 August, stars were observed as follows: at 0840 Sirius (mag. -1.6), 0905 Rigel (mag. 0.3), 1130 Capella (mag. 0.2), 1400 Arcturus (mag. 0.2), 1515 Spica (mag 1.2), and at 1535 Vega (mag. 0.1). Dr. Tousey states that with a polarizer fitted to the telescope, all these stars were "very easy" to find, with the exception of Vega, which he describes as "easy" to locate. In addition to a polarizer, a telescope used for the daylight observation of stars should be fitted with a reticle at infinity, to assist the eye in maintaining focus at infinity.

During this program, Arcturus was observed at high altitude well

after sunrise, and Sirius before sunset with a 20 power telescope fitted to a marine sextant. However, the light absorbtion in the sextant mirrors is too great to make such observations practical with a sextant in its present form.

The design of the sextant could be modified to make daylight star observations feasible. The star would be observed directly, rather than as a reflected image, and the image of the horizon would be brought up to the star by means of the index mirror. This would require a rearrangement of the mirrors on the sextant. The high power telescope would be fitted with a polarizer and a reticle, as described by Dr. Tousey. In addition, it should have two or three interchangeable prismatic eye-pieces, such as are used with the telescopes of fine transits, to facilitate the observation of stars situated well above the horizon. Such an instrument, intended onlyfor celestial navigation, might well be made as an octant, measuring altitudes only to 90 degrees, the scale being lengthened slightly to give a negative reading or reading "off the scale" to determine index error. The markings on the arc would be reversed from those on the ordinary sextant, the zero mark being at the end of the arc away from the observer.

The fixed mirror would belocated in the 45 degrees - 90 degrees sector of the frame; this would necessitate swinging the index arm on the underside of the frame. This mirror could be made rather narrow in the horizontal axis, as the illumination of the horizon during daylight would be strong enough to give a good image; it should probably be without the clear glass portion usually found on the horizon mirrors of conventional sextants.

II THE DIP METER

The dip meter is considered to be a necessary adjunct to the sextant for refined navigation. The Gavrisheff dip meters used during the latter part of this program proved of great value, and are superior in design to similar instruments encountered. A most desirable feature of the Gavrisheff instrument is that any index error is cancelled by rotating the device through 180 degrees about the optical axis of the telescope, between readings.

It is strongly recommended that the dip meter be studied with a view to improving its optics, and facilitate its use at sea. In the Gavrisheff dip meters presently available, the light absorption on the inverted horizon is sufficient to make observations difficult under certain conditions of light. This should be corrected, if possible.

The placement of the knobs or wheels for bringing the two horizons into coincidence should be so arranged that the dip meter is equally convenient to use in either the erect or inverted position.

The qualities of the telescope or telescopes to be used with the dip meter should be determined. It would seem desirable in the interests of simplicity to design interchangeable telescopes which fit both the dip meter and the sextant if the same telescope is equally satisfactory on both instruments. It should be noted that the highest power telescope (16X) available for use with the dip meter gave the best results.

III SIGHT REDUCTION

During the past 35 years almost all effort in the field of celestial navigation has been directed towards shortening the time required for the reduction of sights; to attain speed, it was felt that some accuracy could well be sacrificed. For general use this was correct; the accuracy obtainable with the "short methods" was sufficient for the requirements of ordinary navigation.

Today, however, there is an urgent need in some specialized fields to obtain the maximum degree of accuracy in position fixing by celestial as well as by other navigational means. For celestial navigation improved sextants and telescopes as well as dip meters are now available, which give greatly improved accuracy, as compared to what could be obtained with similar instruments in the past.

The instruments are available for refined celestial navigation; data for the accurate and rapid reduction of sights should also be made available for those areas and times when such navigation is required. As has been noted in the body of this report, the Nautical Almanac does not give sufficient accuracy when a position must be fixed with an error not exceeding 0.2 miles.

For such use, it is recommended that data on hour angle, declination, etc., be made available in readily usable form, and with an end accuracy of 0.05 minutes of arc.

An electronic computer can be used to store these data, as well as to complete the reduction of sights with speed and accuracy. Lacking

such a device, it is recommended that an electric computer be employed to solve the spherical triangle, by means of the standard sin-cosin formulae. It is recommended that natural functions be employed, rather than logarithms. The functions should be stated at least to six decimal places, and for every tenth of a minute of arc. Such a table could readily be prepared from the U. S. Coast and Geodetic Survey, eight place tables, which are tabulated for every second of arc.

IV SELECTION OF THE OBSERVER

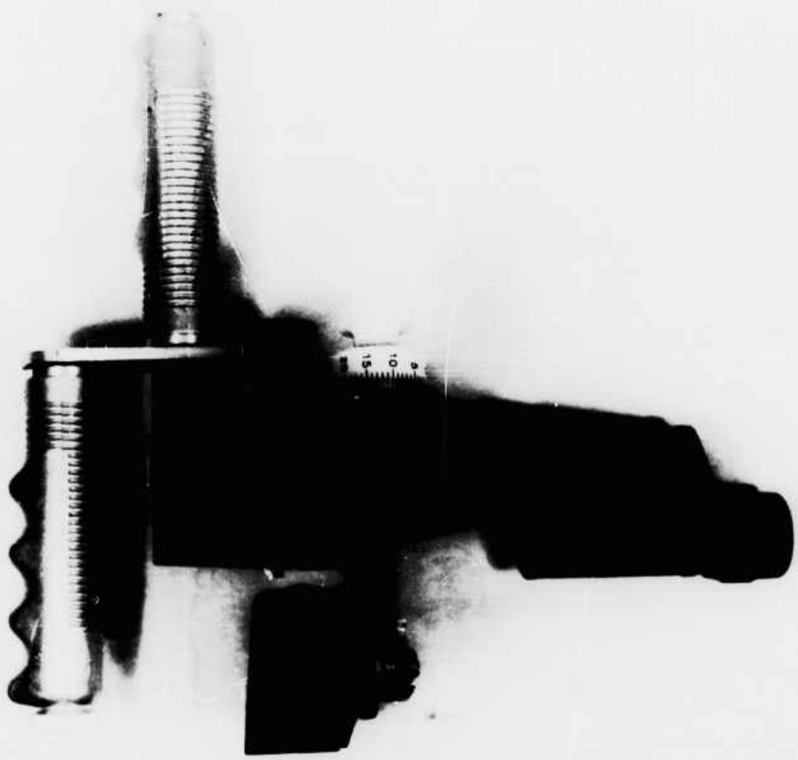
It has been almost universal practice afloat for the ship's navigator to make the great majority of the required celestial observations. The navigator is selected on the basis of his professional knowledge; his visual accuity is rarely considered. This program, as well as similar studies in the past have clearly indicated that skill in the use of the sextant varies greatly between individuals, even those of apparently equally good vision, and equally practiced in the use of the instrument. A limited percentage of individuals have the ability to pick up a star in a bright sky with the sextant long before the majority are able to locate it. In addition only a small number have the ability of judging the instant of contact between the bodyand the horizon. For refined navigation, the observer should excel in both these skills.

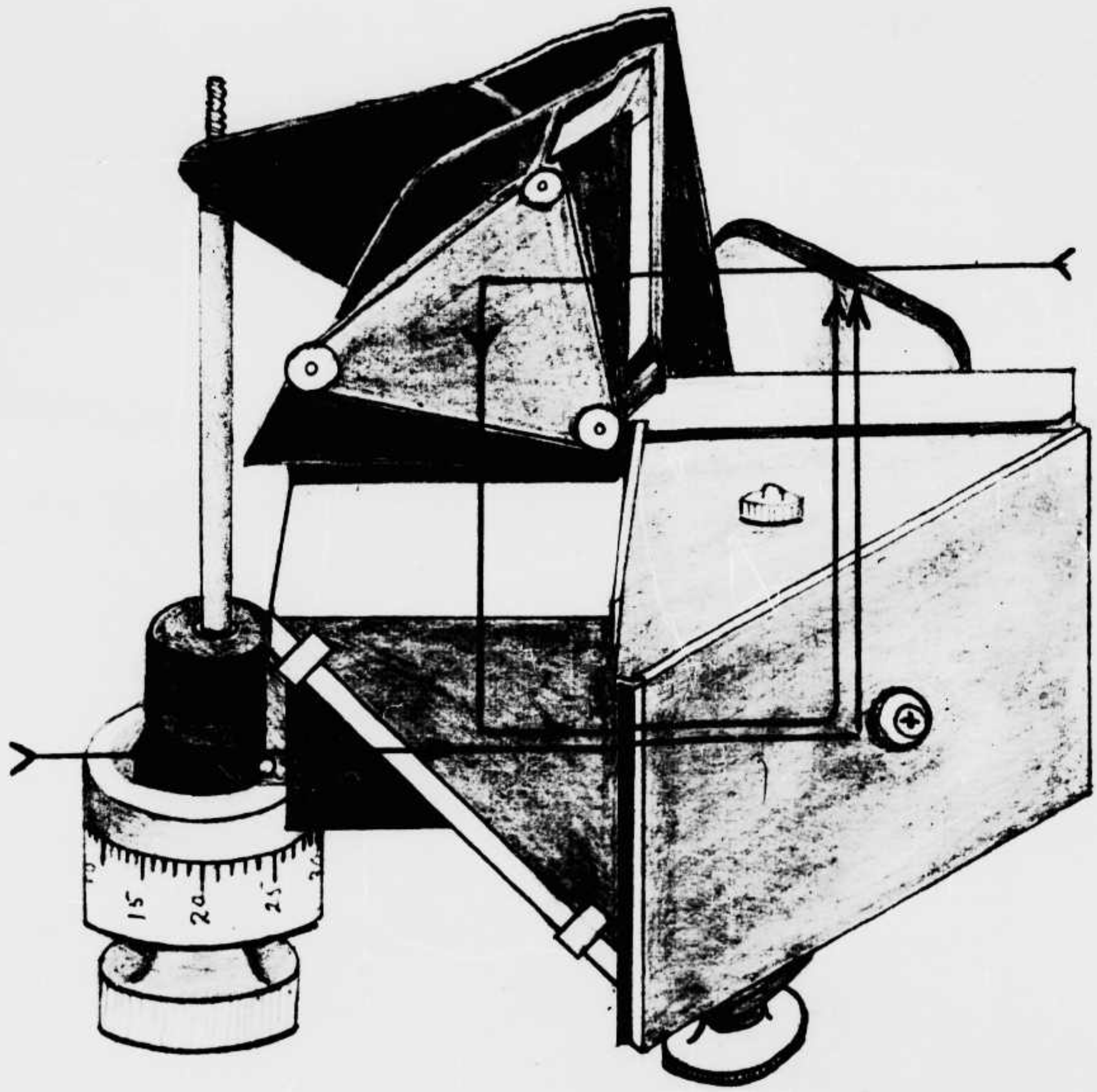
It is urgently recommended that where accuracy in navigation is of paramount importance, the observer be selected solely on the basis of the results he obtains with the sextant; the data he obtains can be processed by others, qualified in that field.

UPPER PHOTOGRAPH. Precision sextant, fitted with a telescope with 50 mm objective lens, and interchangeable eye pieces, giving a magnification of 20x, and 7x.

LOWER PHOTOGRAPH. Gavrisheff dip meter, fitted with a 16 x 50 telescope.

THE PHOTOGRAPH ON THE FOLLOWING PAGE illustrates the optics of the Gavrisheff dip meter.

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